# RADIO EMISSIONS ASSOCIATED WITH SHOCK WAVES AND A BRIEF MODEL OF TYPE II SOLAR RADIO BURSTS

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**Abstract**

In this paper, we discuss the generation of radio waves at shock waves. Two cases are considered. One is associated with a quasi–perpendicular shock and the other is with a quasi–parallel shock. In the former case, it is stressed that a nearly perpendicular shock can lead to a fast Fermi acceleration. Looking at these energized electrons either in the deHoffmann–Teller frame or the plasma frame, one concludes that the accelerated electrons should inherently possess a loss–cone distribution after the mirror reflection at the shock. Consequently, these electrons can lead to induced emission of radio waves via a maser instability. In the latter case, we assume that a quasi–parallel shock is propagating in an environment which has already been populated with energetic electrons. In this case, the shock wave can also lead to induced radiation via a maser instability. Based on this notion, we describe briefly a model to explain the Type II solar radio bursts which is a very intriguing phenomenon and has a long history.

## 1 Introduction

An interesting theoretical issue is how radio emission processes can be induced or triggered by shock waves under various physical conditions. In this article, we present a discussion which comprises two parts. The first part is concerned with a nearly perpendicular shock. In this case, the shock can energize a fraction of the thermal electrons or suprathermal electrons to much higher energies by means of a fast Fermi process. It is possible that under certain conditions these accelerated electrons can lead to radio emission via a maser instability. The second part deals with the situation in which a quasi–parallel shock propagates in an environment which has been populated by energetic electrons. In this case, the shock wave acts like a moving magnetic mirror and may reflect electrons in both upstream and downstream regions. Consequently the reflected electrons, which possess a loss–cone distribution function in velocity space, can lead to a maser instability, provided

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that some other necessary conditions are satisfied. We suggest that this case may be very relevant to the Type II solar radio bursts. A discussion along this line will be addressed later. The organization of the paper is as follows. In Section 2, we briefly review the highlights of the maser instability which is essential in the models to be considered later. We then examine the case of a nearly perpendicular shock and the case of a quasi–parallel shock in Section 3. In Section 4, we suggest a scenario for Type II solar radio bursts. Finally, summary and conclusions are presented in Section 5.

## 2 A brief review of highlights of maser instability

Initiated by Wu and Lee [1979] in an article which discusses the generation mechanism of the auroral kilometric radiation, a cyclotron maser instability due to the presence of a loss–cone distribution of suprathermal electrons has attracted considerable interest. The basic theory of the cyclotron maser instability has been advanced significantly since then. (Relevant bibliography can be found in the review article by Wu [1985] and a most recent discussion by Ladreiter [1991]). Besides the cyclotron maser instability which amplifies radiation near the electron cyclotron frequency, a synchrotron maser instability for a ring–beam or loss–cone distribution function is also possible [Wu et al., 1985; Yoon, 1990a,b; Yoon and Varban, 1990] which amplifies radiation at frequencies about twice the electron plasma frequency. The cyclotron maser instability occurs in a plasma in which the plasma frequency is lower than the cyclotron frequency and, on the other hand, the synchrotron maser instability operates in a plasma in which the plasma frequency is higher than the cyclotron frequency and the frequency band covers a finite number of cyclotron harmonics. For both maser instabilities, it is necessary to have a distribution function $\mathrm{F}_e$ of the suprathermal electrons with an “inverted population”, i.e.

$$\frac{\partial F_e}{\partial v_\perp} > 0 \quad \text{for a finite range of } v_\perp. \tag{2.1}$$

It is obvious that both a loss–cone distribution and a ring–beam distribution satisfy such a condition. However, for the cyclotron maser instability, the required characteristic energy of these electrons can be as low as one kilo–electron Volt, whereas for the synchrotron maser instability, in order to obtain significantly high growth rate, the required electron energy is much higher, if the ratio

$$\epsilon \equiv \frac{\text{Electron plasma frequency}}{\text{Electron cyclotron frequency}} \gg 1. \tag{2.2}$$

When the ratio $\epsilon$ is close to unity, the instability is basically a cyclotron maser instability, as discussed by Freund et al. [1983] and Wu and Freund [1984]. Although in this case radiation with frequencies near the first three cyclotron harmonics can be excited, the growth rate at the third harmonic is usually very small and uninteresting.

## 3 Possible radio emission process at a quasi–perpendicular shock wave

In the case of a nearly perpendicular shock wave, the shock wave propagates along the upstream ambient magnetic field with a very large effective velocity which can be many times the flow velocity [Potter, 1981; Wu, 1984; Leroy and Mangeney, 1984; Krauss–Varban et al., 1989]. If one chooses to work in the deHoffmann–Teller frame and assumes that the electron magnetic moment is conserved, the magnetic field increase at the shock can reflect the upstream electrons due to a magnetic mirror effect. In other words those electrons outside the loss cone in velocity space can be accelerated by this process. After the reflection, these electrons can attain an average velocity approximately twice the effective shock velocity. The basic principal of this energization process is schematically described in Figure 1. Since the effective shock velocity, $V_s$, along the upstream magnetic field is inversely proportional to the cosine of the angle between the shock normal and the magnetic field, $\theta_{nB}$, it is easily seen that the acceleration process is particularly efficient at a nearly perpendicular shock. As previously suggested in Wu [1984], these energized electrons, which possess a ring–beam type distribution, can result in a maser instability, provided that the characteristic pitch angle of the ring–beam distribution is sufficiently large; for example, when the shock is weak.

## 4 Possible radio emission process at a quasi–parallel shock wave and a model of Type II solar radio bursts

If the shock wave is quasi–parallel, the shock wave velocity along the magnetic field lines is only several times the local Alfvén speed, and it is clear that the electron acceleration process which we have just discussed in the case of a quasi–perpendicular shock wave does not occur. However, in this case, something interesting can happen. To proceed with the discussion, we should first discuss briefly some relevant physical properties of quasi–parallel shock waves.

From the general Rankine–Hugoniot conditions, one can see readily that the magnetic field jump across a quasi–parallel shock is very small [Tidman and Krall, 1971]. However, recent numerical simulations based on a hybrid code (which treats ions as particles but electrons as massless fluid) have shown that enhanced magnetic fields occur in the shock transition layer. In addition, it is found that when the Alfvén Mach number is low, say 2 or lower, the magnetic field gradient is much steeper in the leading edge than that in the downstream side. On the other hand, when the Alfvén Mach number is sufficiently high, say 4 or higher, the magnetic field gradients in both upstream and downstream sides are steep. For the purpose of illustration, we present Figure 2 in which two cases are taken from the paper by Mandt and Kan [1990]. These results are obtained for case (b): plasma beta equals 0.5. In panel (a) the shock has an Alfvén Mach number equal to 4. In this case, we see that an enhanced magnetic field profile occurs in the shock layer such that a jump $\delta$B about three times and a density jump about four times of the upstream values take place. Similarly in panel (b) the shock has an Alfvén Mach number equal to

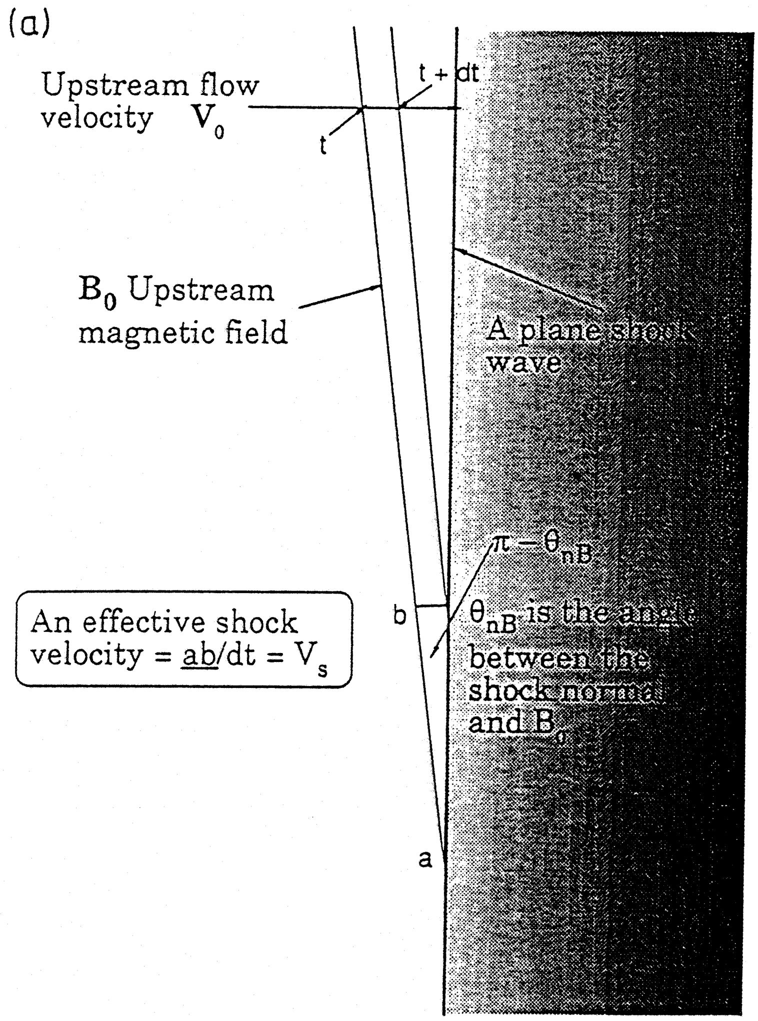
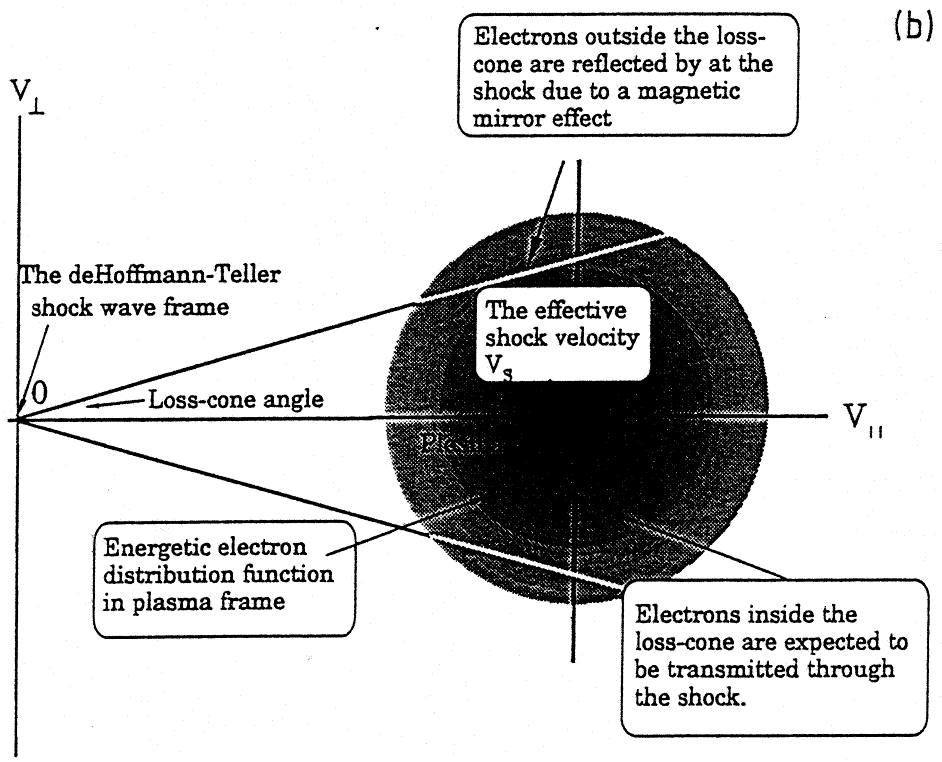



*Figure 1: (a) Definition of the effective shock velocity, $V_s$, along the upstream magnetic field. It is seen that $V_s$ is proportional to $V_0/\cos\theta_{nB}$. Thus for a nearly perpendicular shock, the effective velocity can be very large. (b) Mirror reflection process at the shock. The loss–cone angle is defined by the magnetic field increase at the shock. Electrons outside the loss cone can be reflected. After the reflections, in the plasma frame, these electrons can have an average velocity about twice of the effective velocity $V_s$. Consequently, the reflected electrons are energized. Note that these electrons inherently have a ring–beam distribution function.*



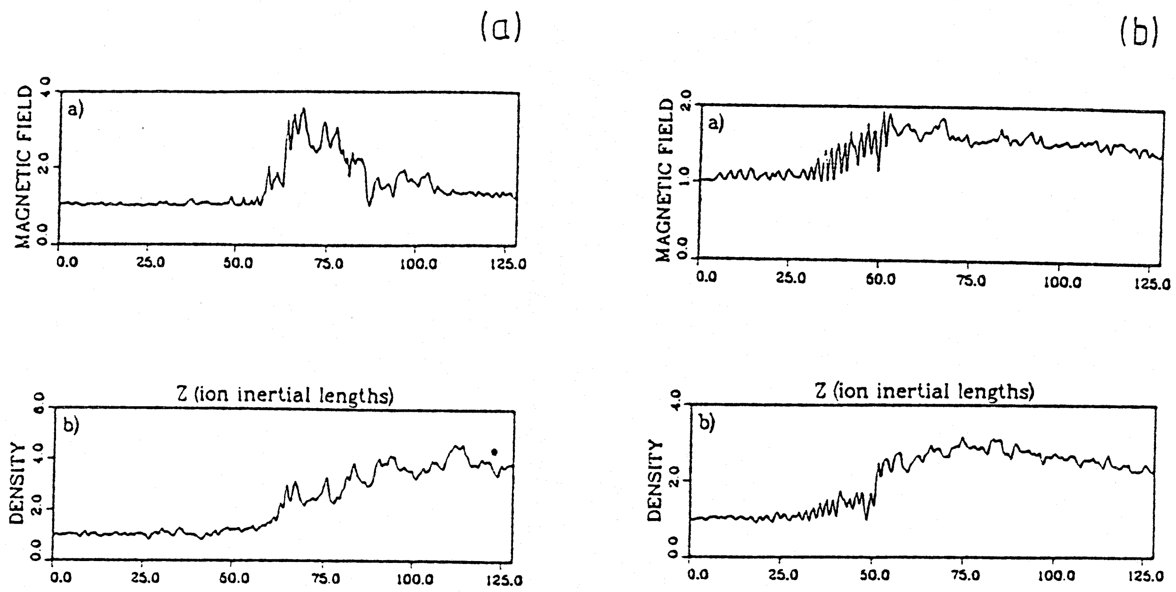



*Figure 2: Results of numerical simulations of quasi–parallel shock waves. The angle $\theta_{nB}$ is considered to be 10° and plasma beta is taken to be 0.5. Case (a) the Alfvén Mach number is 4 and (b) the Alfvén Mach number is 2. Of particular interest is that when the Mach number is 4 or higher, the magnetic field gradients on both the upstream and downstream sides are steep whereas when the Mach number is 2 or lower only the magnetic field gradient on the leading side is steep.*

2. Several very interesting and important points should be mentioned and summarized below.

First, under certain conditions, reflection of electrons can result in loss–cone velocity distributions in both upstream and downstream regions.

Second, it is well known in the theory of collisionless shock waves that, when the beta value of the upstream is less than unity, the density jump can be described as

$$\frac{\rho_1}{\rho_2} = \frac{1}{4}\left[1 + O\left(\frac{1}{M^2}\right)\right] \tag{4.1}$$

where $\rho_1$ and $\rho_2$ denote the upstream and downstream density, respectively. Thus, when M $> 3$, the density ratio $\rho_1/\rho_2$ is approximately 4. This conclusion is true for arbitrary direction of shock normal.

Third, following the preceding point, we see that for a sufficiently high Mach number shock the plasma frequency in the downstream region is twice the value of that in the upstream region. Thus, if the synchrotron maser instability is operative in both upstream and downstream regions, then one may see two emission bands such that the characteristic frequencies differ approximately by a factor of 2.

Fourth, if the Mach number is comparable to or lower than 2, the maser instability may not be operative in the downstream due to the small gradient there. Therefore, although

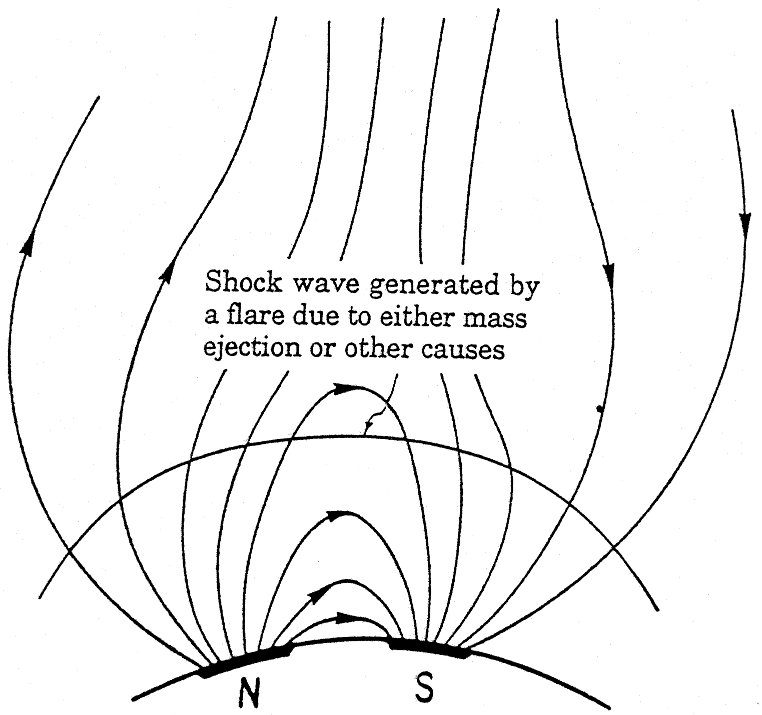



*Figure 3: A model situation high above the active regions. There are two regions; one has open field lines and the other has closed field lines. A shock wave due to a flare propagating upward is shown.*

in this case the plasma frequencies in the two regions may have a ratio equal to or less than $\sqrt{2}$, it does not matter since only the upstream emission is observable.

All these points are relevant and essential to the model, which we are proposing, of the Type II solar radio emission [ Kundu, 1965; Zheleznyakov, 1970; Kundu, 1982; Nelson and Melrose, 1985]. In the following, let us describe the essence of the scenario.

We assume that the source region of the Type II emission is above the active region near a flare. For the purpose of illustration, the situation is shown in Figure 3. Moreover, we consider that the region has been populated with energetic electrons before the shock is formed. The existence of these energetic electrons is evidenced by the hard X–ray emission [e.g. de Jager et al., 1986 ] and radiation of centimeter wavelengths which are extensively discussed in the literature [ see Kundu, 1965 ]. The energies of these electrons may range from several tens of keV to several hundred keV, as have been estimated. It is seen that over a large region the shock wave is quasi–parallel. We are particularly interested in the region where the field lines are closed. The quasi–parallel shock wave can reflect those electrons outside the velocity loss cone in front of and/or behind the quasi–parallel shock. Indeed, in this case, the shock velocity along the ambient magnetic field, $V_s$, is in general much smaller than the mean velocity of these energetic electrons. It can be easily envisioned that the reflected electrons may have a ring–beam type distribution which can lead to a maser instability. Since the source region of Type II bursts usually are believed to occur sufficiently high above the chromosphere where the electron plasma frequency is higher than the electron cyclotron frequency, we believe that the synchrotron maser instability may be responsible for the observed radiation.

## 5 Discussion and conclusion

Admittedly the above description of the model for Type II emissions is very brief and terse. A more detailed discussion will be given in a forthcoming article. The purpose of this preliminary report is to outline the essence of a new scenario which may qualitatively explain the main features of the Type II radio emissions. In the following, a brief discussion is given.

First, it is important to point out that the present model inherently explains the issue why the source of emission is closely associated with the shock. As a result, the propagating velocity of the shock determines the frequency drift of the main source.

Second, the model interprets the "fundamental" and "harmonic" bands in a very different context, as remarked earlier. Third, the maser instability may not be operative in those subregions where the energetic electrons are not reflected and thereby the distribution function has no loss–cone feature. The central region is a good example. This point may lead to the feature of band splitting.

Fourth, the model may explain the multiple lanes. If the sources of energetic electrons are discrete in the foot regions of the closed field lines, then only along those field lines connecting to the sources of the energetic electrons can the emission take place. This may cause the multiple lanes observed.

One final remark is that the model may be extended conceptually to explain interplanetary Type II radio emissions, since energetic electrons may be trapped in the upstream and/or downstream regions of an interplanetary shock. However, since we know that in interplanetary space the ratio of plasma frequency to cyclotron frequency is large, a further study of the synchrotron maser instability in this regime is necessary. Such an investigation is currently in progress.

## References

de Jager, C., M. E. Bruner, C. J. Crannel, B. R. Dennis, J. R. Lemen, and S. F. Martin, in The Solar Maximum Mission Flare Workshop Proceedings, *Energetic Phenomena on the Sun*, edited by Kundu M. and Woodgate B., NASA Conference Publication **2439**, p. 5–5, 1986

Freund, H. P., H. K. Wong, C. S. Wu, and M. J. Xu, An electron cyclotron maser instability for astrophysical plasmas, *Phys. Fluids*, **26**, 1983.

Krauss–Varban, D., D. Burgess, and C. S. Wu, Electron acceleration at nearly perpendicular collisionless shocks; 1. one dimensional simulations without electron scale fluctuations, *J. Geophys. Res.*, **94**, 15089, 1989.

Kundu, M. R., *Solar Radio Astronomy*, ( New York: Wiley Interscience), 1965.

Kundu, M. R., Advances in solar radio astronomy, *Rept. Prog. Phys.*, **45**, 1435, 1982.

Ladreiter, H. P., The cyclotron maser instability: Application to low–density magnetoplasmas, *Astrophys. J.*, **370**, 419, 1991.

Leroy, M. M., and A. Mangeney, A theory of energization of solar wind electrons by the Earth's bow shock, *Ann. Geophys.*, **2**, 449–456, 1984.

Mandt, M. E, and J. R. Kan, Dispersive and viscous scale lengths in the two–stage ion heating at quasi–parallel collisionless shocks, *J. Geophys. Res.*, **95**, 6353, 1990.

Nelson, G. L., and D. B. Melrose, Type II bursts, in *Solar Radiophysics*, edited by McLean and Labrum, Cambridge University Press, New York, 1985.

Potter, D. W., Acceleration of electrons by interplanetary shocks, *J. Geophys. Res.*, **86**, 11111, 1981.

Tidman, D., and N. A. Krall, Shock Waves in Collisionless Plasmas, Wiley–Interscience, New York, 1971.

Wu, C. S., A fast Fermi process: Energetic electrons accelerated by a nearly perpendicular bow shock, *J. Geophys. Res.*, **89**, 8857–8862, 1984.

Wu, C. S., Kinetic cyclotron and synchrotron maser instabilities: Radio emission processes by direct amplification of radiation, *Space Sci. Rev.*, **41**, 215–298, 1985.

Wu, C. S., and L. C. Lee, A theory of the terrestrial kilometric radiation, *Astrophys. J.*, **230**, 621–626, 1979.

Wu, C. S., and H. P. Freund, A kinetic cyclotron maser instability associated with a hollow beam of electrons, *Radio Sci.*, **19**, 519–525, 1984.

Wu, C. S., G. C. Zhou, and J. D. Gaffey (Jr.), Induced emission of radiation near $2\omega_e$ by a synchrotron–maser instability, *Phys. Fluids*, **28**, 1985.

Yoon, P. H., Amplification of a high–frequency electromagnetic wave by a relativistic plasma, *Phys. Fluids B*, **2**, 867, 1990a.

Yoon, P. H., The effect of background temperature on the synchrotron maser process, *Phys. Fluids B*, **2**, 1662, 1990b.

Yoon, P. H., and D. Krauss–Varban, Gyroharmonic maser instability for weakly relativistic electrons with a loss–cone distribution, *Phys. Fluids B*, **2**, 1918, 1990.

Zheleznyakov, V. V., Radio emission of the Sun and planets, *Pergamon Press*, New York, 1970.